

# Hybrid Beamforming Strategies for mm-Wave Massive MIMO System

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## Abstract

*Hybrid analogue and digital beamforming (HBF) has emerged as a compelling solution for millimetre-wave (mm-wave) communication systems, addressing the need for efficient beamforming while minimizing hardware costs and power consumption. We optimise HBF for mm-wave Massive MIMO systems in the present study, using the Spectral efficiency and bit rate error as the performance metrics to assess transmission reliability. To reduce computational complexity, we introduce a low-complexity singular value decomposition and orthogonal matching pursuit-based HBF algorithms for mm-wave massive MIMO systems. Simulation results demonstrate that our proposed HBF algorithms exhibit significant performance improvements over existing methods.*

**Keywords:** Hybrid beam-forming, millimetre-wave communication, bit error rate, spectral efficiency, singular value decomposition (SVD), multiple input multiple output (MIMO).

## INTRODUCTION

An array of several antennas is used in beamforming, a radio frequency signal processing approach, to transmit and receive directional signals. To achieve spatial selectivity, beamforming can be used at both the transmitting and receiving ends. It is used in communication, radar, sonar, and acoustics. In addition, Beamforming is employed in Wi-Fi networking and 5G. Beamforming is a technique used to control the direction of radio waves or sound waves. It essentially focuses a signal in a specific direction, rather than broadcasting it omnidirectional (in all directions). This provides a number of benefits for different applications. Signal focussing is when a torch beam illuminates a certain area rather than illuminating everywhere. Beamforming does the same thing with radio waves or sound waves, directing them towards a desired location. Improved Signal Strength i.e., by focusing the signal, beam-forming strengthens it in the target direction. Clearer communication and improved reception result from this.

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*Reduced interference:* Beamforming can also suppress unwanted signals arriving from other directions. This reduces noise and interference, resulting in improved signal quality. Additionally, beamforming can be utilised to dynamically modify the beam direction in response to environmental changes, such as user movement or modifications to the radio frequency (RF) surroundings [1].

In recent years, the demand for high-speed wireless communication has surged exponentially, driven by the proliferation of mobile devices, Internet of Things (IOT) applications, and emerging technologies such as augmented reality and autonomous vehicles. To meet these growing demands and overcome the limitations of

conventional wireless systems, researchers tend to be narrower than that of an offset-fed antenna. Signal Strength i.e., by focusing the signal, beamforming strengthens it in the target direction. Improved reception and clearer communication result from this [2].

Fundamentally, Massive MIMO uses a lot of antennas at the base station to service many users at once, taking use of the spatial dimension to significantly improve performance. Spatial multiplexing is the fundamental idea of Massive MIMO, in which the base station uses its many antennas to send numerous data streams to multiple consumers using the same frequency-time bandwidth [3]. By carefully controlling the phase and amplitude of the transmitted signals, Massive MIMO can mitigate inter-user interference and achieve substantial improvements in spectral efficiency.

Moreover, Massive MIMO introduces beam-forming techniques that enable precise targeting of signals towards intended users while suppressing interference from other directions. This directional transmission not only enhances signal quality but also increases the system's resilience to channel fading and environmental disturbances.

One of the defining features of Massive MIMO is its ability to operate in the mm-wave frequency bands, which offer significantly larger bandwidths compared to conventional sub-6 GHz frequencies. By harnessing the abundant spectrum available in mm-wave bands, Massive MIMO systems can achieve multi-gigabit data rates, paving the way for ultra-fast and low-latency wireless networks [4].

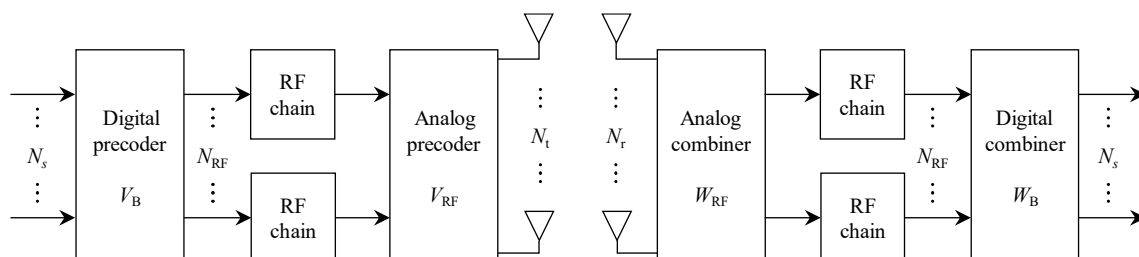
This study is organized as follows: for the ease of presentation, we start with the antenna configuration with MIMO antenna system and introduce the system model along with the HBF problem formulation. Then, we present the basic idea and the optimization procedure, and propose the SVD-HBF and OMP-HBF algorithms to maximize the spectral efficiency and minimize bit error rate.

## IMPLEMENTATION

A  $N_t$ -element square array with  $N_{RF}$  RF chains on the transmitter side and a  $N_r$ -element square array with  $N_{RF}$  RF networks on the receiver side are both components of a  $N_t \times N_r$  MIMO hybrid beam-forming system. Suppose that every antenna is linked to every RF chain. As a result, a phase changer is linked to each antenna. Hybrid beam-forming system shown in Figure 1. By dividing the array aperture into four fully connected subarrays, one can simulate such an array. The transmitter (TX) antenna array is defined as a uniform rectangular array (URA) with dimensions  $\sqrt{N_t} \times \sqrt{N_t}$ , spaced half a wavelength apart. The sub array selection parameter specifies that all antenna elements are connected to each RF chain ( $N_t N_{RF}$ ). Similarly, the receiver (RX) antenna array is also defined. The parameters are similar to those of the transmitter array, but the dimensions and number of RF chains may differ ( $N_r, N_r N_{RF}$ ).

### Channel Model

A channel model describes the behaviour of a communication channel through which signals propagate from a transmitter to a receiver. It captures the effects of various factors such as propagation environment, transmitter and receiver characteristics, interference, noise, and signal impairments. Channel models are essential for designing and evaluating communication systems, understanding their performance, and



**Figure 1.** Hybrid beam-forming system.

developing techniques to mitigate channel impairments. The channel matrix  $H$  is based on the specified scattering scenario, incorporating the spatial characteristics of the antenna arrays and the scattering environment. The resulting channel matrix represents the complex channel gains between each transmit antenna and each receive antenna, accounting for the effects of multipath propagation, scattering, and antenna geometry [5].

### Hybrid Weights Computation

A set of precoding weights modulates the signal, which is then transmitted via the channel and retrieved by a set of combining weights in a spatial multiplexing system with all-digital beamforming. The procedure can be expressed mathematically as  $Y=(XFH+N).W$ , where  $N$  is a  $N_r$ -column matrix with receiver noise at every component,  $Y$  is a  $N_s$ -column matrix with recovered data streams in its columns,  $X$  is a  $N_s$ -column matrix with data streams in its columns,  $F$  is a  $N_s \times N_t$  matrix representing the precoding weights, and  $W$  is a  $N_r \times N_s$  matrix representing the combining weights. Since the system's objective is to improve spectral efficiency, determining the precoding and combining weights can be viewed as an optimisation problem. The ideal precoding and combining weights transform the product of  $FHW$  into a diagonal matrix, allowing for the independent recovery of each data stream. The signal flow in a hybrid beamforming system is comparable. Baseband digital weights and RF band analogue weights are used to create the precoding weights and the combining weights. Incoming data streams are converted to input signals at each RF chain by the baseband digital weights, and the signal at each RF chain is further converted to the signal radiated or collected at each antenna element by the analogue weights [6].

### HBF-ALGORITHMS

#### Singular Value Decomposition Based-HBF

SVD comes in at the digital precoding stage. It decomposes the channel matrix ( $H$ ), which represents the complex gains between antennas and users, into two components:

1.  $U$ : A unitary matrix representing the left singular vectors.
2.  $\Sigma$ : A diagonal matrix containing the singular values, which capture the channel's strength along different spatial directions.

The right singular vectors are represented by a unitary matrix called  $V$  (Hermitian conjugate of transposition). A factorisation of  $A=U\Sigma V^T$ , where  $U$  is an orthogonal matrix of size  $m \times m$ , is a singular value decomposition of  $A$ .  $V$  is an orthogonal matrix of size  $n \times n$ . For  $i=1, \dots, r$ , the  $i$ th diagonal entry of the  $m \times n$  matrix  $\Sigma$  equals the  $i$ th singular value  $\sigma_i$ . Every other value in  $\Sigma$  is zero. This decomposition reveals the underlying spatial structure of the channel. The significance of each spatial orientation for the transmission of signals is indicated by the singular values [7].

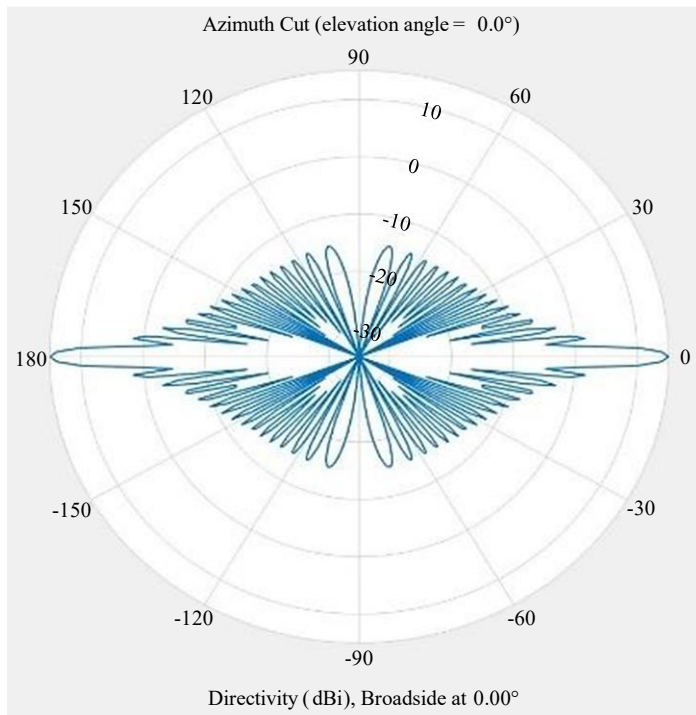
#### Orthogonal Matching Pursuit Based-HBF

Iterative in nature, OMP finds  $x$  element by element in a methodical, iterative fashion. OMP is also a greedy algorithm, solving the problem as best it can at each step using the information available. Assuming that  $A \in \mathbb{R}^{(m \times n)}$  and  $B \in \mathbb{R}^m$ , it is optional to normalise each of  $A$ 's column vectors to the unit norm:  $a_i \leftarrow a_i / (\|a_i\|_2)$ . Because of this normalisation, the absolute value of the dot product (correlation) between any two columns of  $A$  is restricted by 1 and ensured to be within the range  $\{-1, +1\}$ .

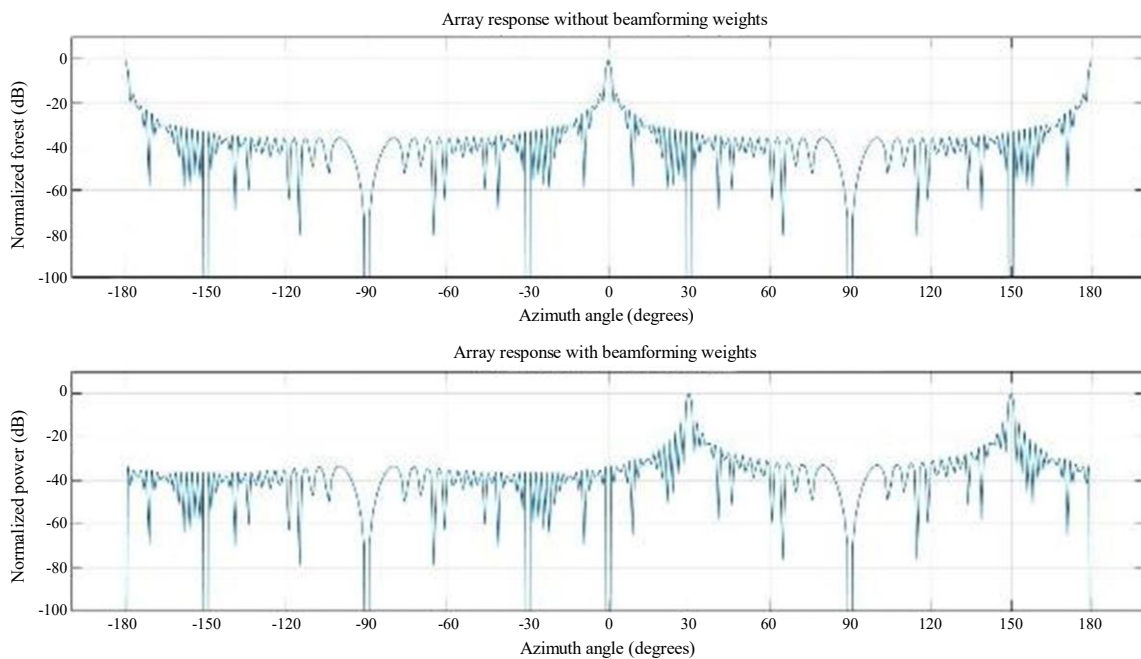
### SIMULATION

#### Beam Pattern

A uniform linear array (ULA) with 32 elements, spaced  $\lambda/2$  apart, is created to represent the antenna array. The frequency range of the array elements is set, and a time vector is generated. A test signal is created with zeros, except for a segment where it is set to 1. Beam pattern for  $32 \times 32$  MIMO system has been shown in Figure 2. The angle of arrival of the signal is specified, and the received signal at the antenna array is computed considering the plane wave signal arrival angle and carrier frequency. Gaussian noise with a specified power level is added to the received signal to simulate real-world conditions. A phased array beamformer is then instantiated, configured with the antenna array [8].



**Figure 2.** Beam pattern for 32x32 MIMO system.



**Figure 3.** Array response.

The most widely used definition of mMIMO is a system in which there are more antennas than users. In actuality, huge refers to a base station with 32 or more logical antenna ports. we can observe when number of antennas increased, Array gain is increased to get maximum information at the receiver.

### Array Response

An antenna array's directionality can be enhanced by beamforming. Array response has been shown in Figure 3 [9, 10]. The two graphs show the normalized power of an antenna array response in decibels (dB) plotted across azimuth angle in degrees.

The x-axis labelled “Azimuth Angle (degrees)” indicates the direction from which the sound wave is coming relative to the centre of the array. The y-axis labelled “Normalized Power (dB)” shows the relative strength of the signal.

### Bit Error Rate

The frequency of errors in data transmission is indicated by the bit error rate, or BER. BER vs. SN0052 has been shown in Figure 4. A more dependable gearbox is indicated by a lower BER. The graph shows the bit error rate (BER) versus the number of antennas for singular value decomposition (SVD) and orthogonal matching pursuit (OMP).

### Spectral Efficiency

The electromagnetic spectrum is a finite resource, and the demand for wireless communication services continues to increase rapidly. Spectral efficiency vs. SNR is shown in Figure 5. The available spectrum

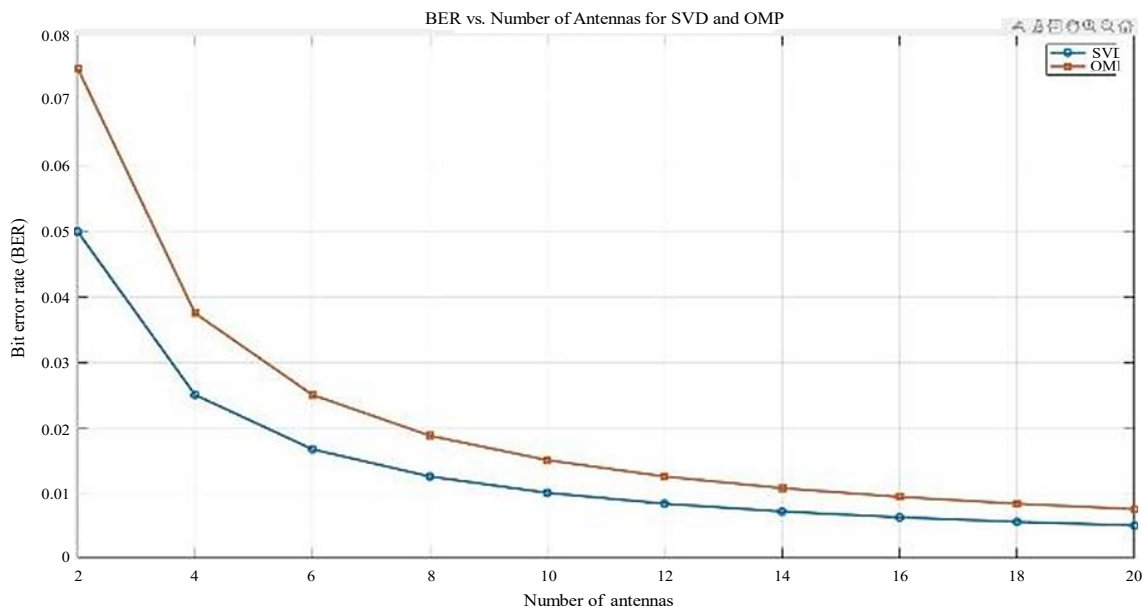


Figure 4. BER vs. SN0052.

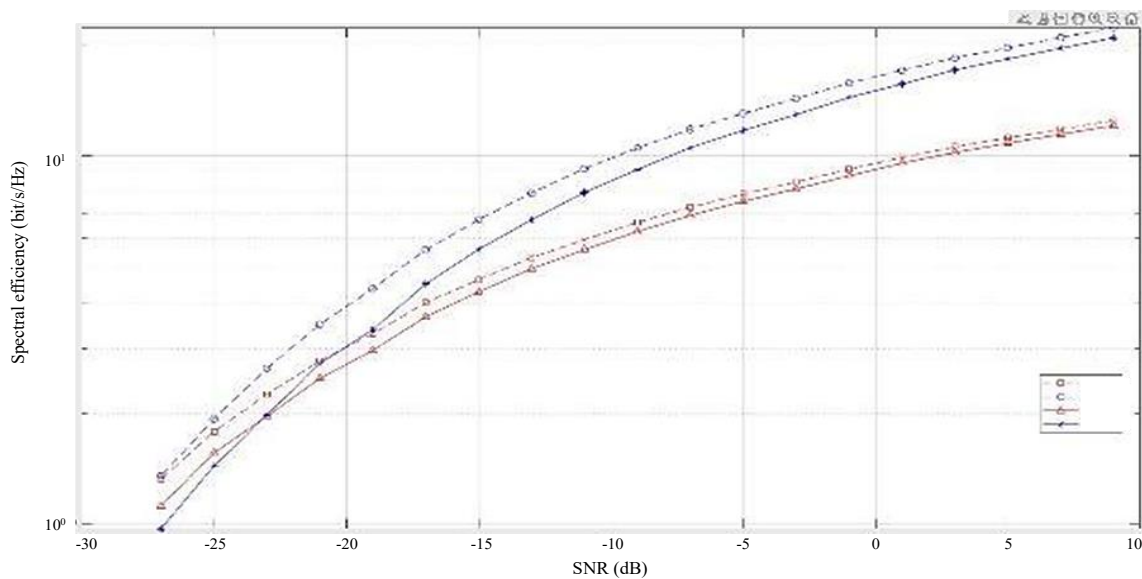
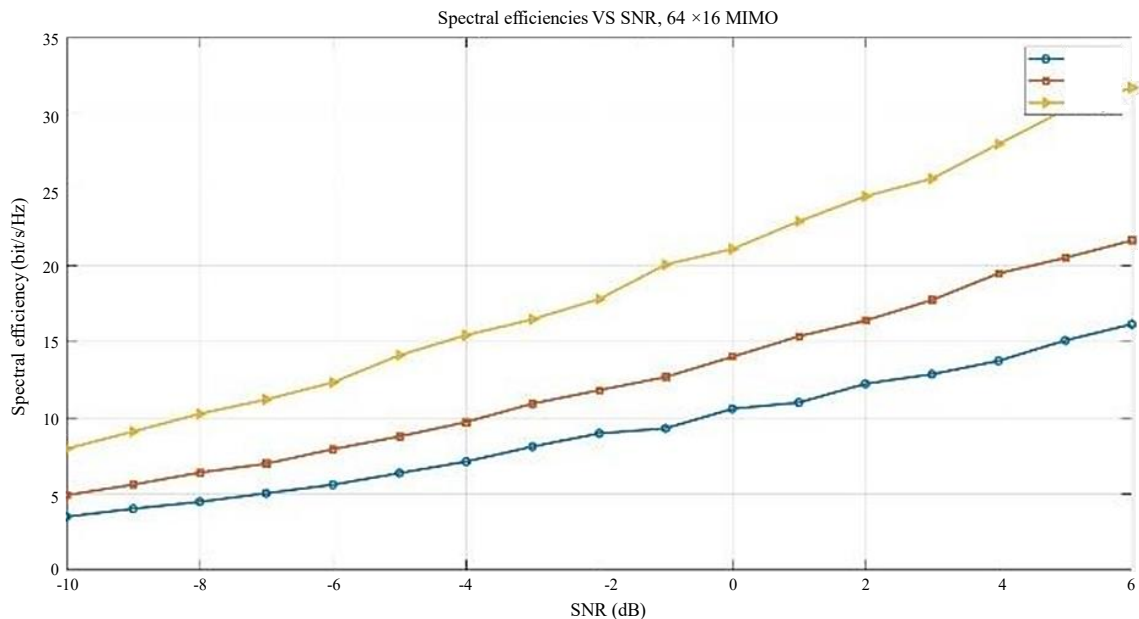


Figure 5. Spectral efficiency vs. SNR.



**Figure 6.** Spectral efficiency vs. no. of antenna elements.

gets more congested as more gadgets and software depend on wireless networking. Improving spectral efficiency allows for more efficient utilization of the limited spectrum resources, enabling the support of a larger number of users and higher data rates within the available bandwidth.

The spectral efficiency appears to increase as the SNR increases. This is because there is less noise to interfere with the signal, so more data can be transmitted per unit of bandwidth. Spectral efficiency vs. no. of antenna elements is shown in Figure 6. The amount of data that may be sent via a communication channel per unit of bandwidth is known as spectral efficiency. Numerous data streams are sent simultaneously via numerous antennas in MIMO systems.

## CONCLUSION

In this study, we investigated the HBF optimization for mm Wave massive MIMO communication systems. Instead of maximizing the spectral efficiency as in most existing works, we took the Singular value decomposition and orthogonal matching pursuit for precoding the matrices to enhance the performance of the system by maximizing the spectral efficiency and minimizing the bit error rate and simulating beam patterns for different MIMO configurations.

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